Fault Detection of Electrical Equipment. Diagnostic Methods

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Abstract

This paper presents an application's experience of Low voltage impulse testing (LVI-testing), some results of the use of Frequency Response Analysis (FRA) to check the condition of transformer windings and infra-red control (IR-control) results of electrical equipment. The LVI method and short-circuit inductive reactance measurements are sensitive for detecting such faults as radial, axial winding deformations, a twisting of low-voltage or regulating windings, a losing of winding's pressing and other. IR-control was used for detection of overheating of disconnector contacts, bushing condition of power transformers, condition of circuit breakers, arresters and limiters of overvoltages, coupling transformers, measuring current transformers, measuring voltage transformers and other. Information-measuring systems (IMS), which described in this paper, were proposed to use together with rapid digital protection against short-circuit regimes in transformer windings.

Keywords

Frequency Response Analysis; Transformer Winding Fault Diagnostic; Low Voltage Impulse Method; Short-circuit Inductive Reactance Measurement; Information-measuring System

Introduction

Failure rate depends on some factors. Winding electrodynamic deformations after short-circuit currents can be resulted in insulation disruption and to turn-to-turn internal short-circuit immediately. But in other cases, the insulation weakness center can probably appear in the winding deformation point. This insulation weakness center can exist in the winding for few years. And an increase of partial discharge (PD) intensity, which will result in insulation disruption and to turn-to-turn short-circuit, is being registered.

LVI-testing, FRA and short-circuit inductive reactance measurements are sensitive for detecting such transformers winding faults as buckling, axial shift and other. The 70 units of 25-240 MVA 110-500 kV power transformers were checked by LVI method. A few power transformers were detected with winding deformations after short-circuit with aperiodical short-circuit current. The block 80 MVA 110 kV transformer had serious amplitude and frequency LVI LV1-LV2 winding oscillogram differences after generator side short-circuit. The low-voltage (LV) winding signal spectrum of 80 MVA 110 kV transformer changed after short-circuit.

22 units of power transformers extending in capacity range from about 25 MVA to over 666 MVA and in voltage range from 110 kV to 750 kV were tested at short-circuit at Togliatti Power Testing Laboratory (Russia) during 1983-1995. The application of LVI method and measurement of inductive reactance deviation allowed to detect a twisting of low-voltage winding and radial winding's deformations at tests of the 400 MVA and a 250 MVA block power transformers [1-5].

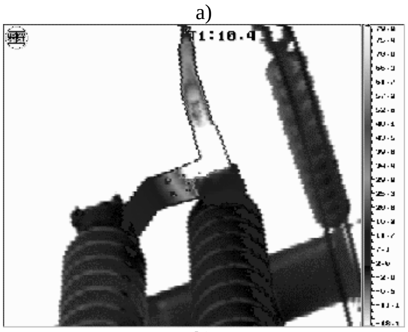
Power transformers are one of the basic parts in the circuitry of power transmission and delivery. Therefore the interest to perfection of the power transformers' fault diagnostic methods is being increased. The repairs of power transformers and other electrical equipment are carried on, using diagnostic measurement results [1, 2, 3, 5-9].

Infra-red control was used for detection electrical equipment's faults, defects and weaknesses: overheating of disconnector contacts, bushing condition of power transformers, condition of circuit breakers, arresters and limiters of overvoltages, coupling transformers, measuring current transformers, measuring voltage transformers, control of connecting heads soldering quality of turbo-generator stator windings during repairing and other.

Infra-red Control Results

An examples of efficient application of infra-red control for electrical equipment faults diagnostic are in the fig. 1 : overheating of disconnector contacts (ΔT=80°C, ΔT=60°C, ΔT=83°C) (a, b, c) and, moreover, it's a crack in porcelain; temperature differences between measuring voltage transformer phases (ΔT=2°C) (d); bad working of transformer cooling system (e); overheating of built-in measuring current transformers at the 110 kV bushings (f); overheating of porcelain local moistening of disconnector (ΔT=15,1°C) (g).

a)



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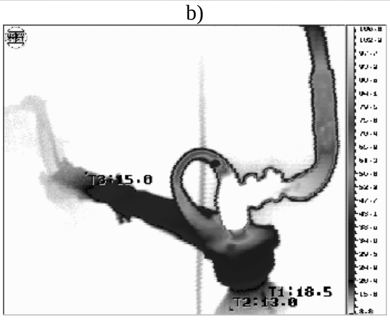

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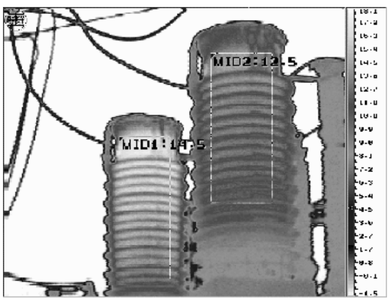

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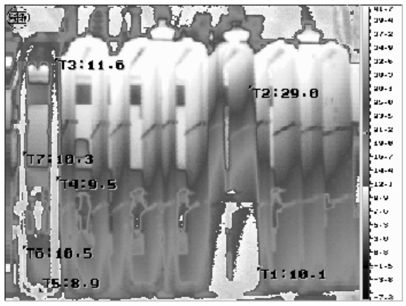

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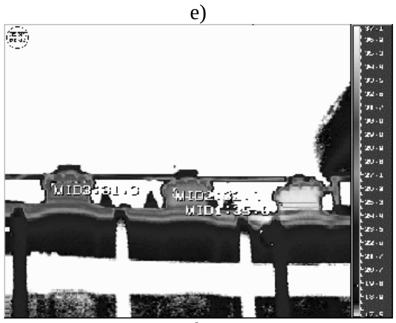

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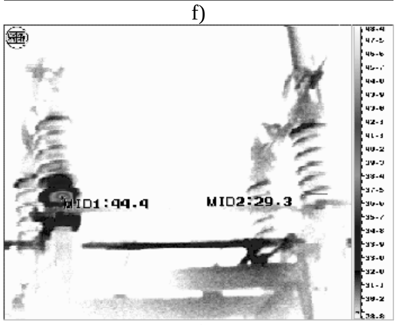


g)

FIG. 1 AN EXAMPLES OF EFFICIENT APPLICATION OF INFRA-RED CONTROL FOR ELECTRICAL EQUIPMENT FAULTS DIAGNOSTIC : a), b), c) - OVERHEATING OF DISCONNECTOR CONTACTS (ΔT=80°C, ΔT=60°C, ΔT=83°C) AND, MOREOVER, c) – CRACK IN PORCELAIN; d) – TEMPERATURE DIFFERENCES BETWEEN MEASURING VOLTAGE TRANSFORMER PHASES (ΔT=2°C); e) – BAD WORKING OF TRANSFORMER COOLING SYSTEM; f) - OVERHEATING OF BUILT-IN MEASURING CURRENT TRANSFORMERS AT THE 110 kV BUSHINGS ; g) – OVERHEATING OF PORCELAIN LOCAL MOISTENING OF DISCONNECTOR (ΔT=15,1°C).

Infra-red control of soldering quality of connecting heads of turbine-driven generator stator windings is very important question for Heat Electric Power Stations in service during repairing. The "Inframetrics" (USA) and "Irtis" (Russia) thermal vision detectors were used. Infra-red control of turbo-generator stator windings was carried out on opened winding overhand of stator without rotor and with previous heating from direct current source, for example, from reserve exciter by 1000 Ampere current. An example of overheating of connecting heads after soldering of turbo-generator stator windings during repairing is presented in the fig.2 (ΔT= 5 degrees C ΔRmax=6,8%, ΔR - ohmic resistance deviation) [8].

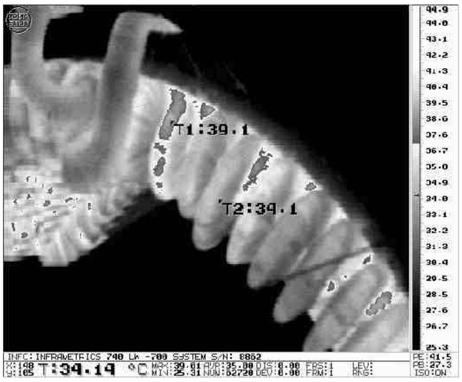


FIG. 2 EXAMPLE OF OVERHEATING OF CONNECTING HEADS BEFORE SOLDERING OF 60 MWatt TURBO-GENERATOR STATOR WINDINGS DURING REPAIRING (VIEW FROM EXCITER)

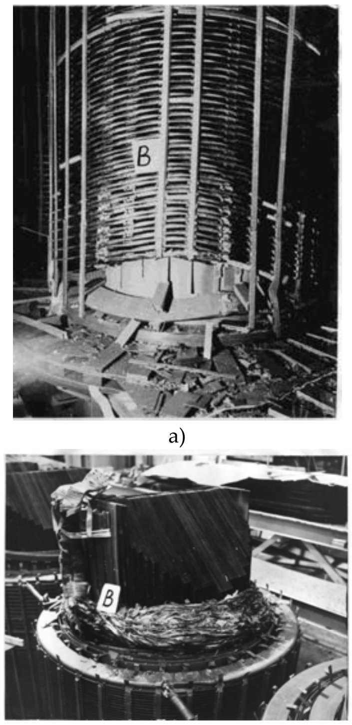
LVI-testing of Transformer's Winding and FRA Method

The damage of regulating winding was detected at the short-circuit tests of link 167 MVA/500 kV/220 kV and 125 MVA/220 kV/110 kV autotransformer at Power Testing Laboratory (Russia). The regulating winding was untwisted at short-circuit tests of 25 MVA railway transformer. The windings of 160 MVA metallurgical transformer were pressed off during these tests. Deformations of turns were detected at the electrodynamic tests of 666 MVA powerfull transformer for the Hydroelectric Power Station [5-11]. The LVI method is very sensitive to small local changes of winding geometry: turn-to-turn and coil-to-coil capacitances, mutual inductances between transformer windings. The LVI oscillograms, which contains basic resonance frequencies of transformer winding, are a "fingerprint" or condition state of transformer. Generally, windings of large power transformers have three basic resonance frequecies. Frequency Response Analysis (FRA) showed presence of 110 kHz, 320 kHz and 550 kHz frequencies for 250 MVA /220 kV transformer. An amplitude of these resonance frequencies changed 1,3-2 times after detection of radial buckling in Low voltage (LV) winding at short-circuit tests (fig.3).

Inductive reactance deviation was Δ Xk= +1% in this case.

The axial shift and damage of pressing system with short-circuit to iron core were detected in the "B" phase LV internal winding of 250 MVA /220 kV transformer after short-circuit tests (fig.4). Inductive reactance deviation was Δ Xk= +20% on the "B" phase [14,16,17].

FIG. 3 TYPICAL EXAMPLE OF DEFORMATION DUE TO RADIAL BUCKLING IN THE "A" PHASE LV INTERNAL WINDING OF 250 MVA /220 kV TRANSFORMER (Δ Xk= +1%).



a)

b)

FIG. 4 EXAMPLE OF DEFORMATION DUE TO AXIAL SHIFT (a) AND DAMAGE OF PRESSING SYSTEM WITH SHORT-CIRCUIT TO IRON CORE (b) IN THE "B" PHASE LV INTERNAL WINDING OF 250 MVA /220 kV TRANSFORMER (Δ Xk= +20%).

During short-circuit the copper wires of transformer winding were deformed under the influence of electromagnetic forces by Biot-Savart's law, which will be in the differential form [10-16]:

$$df = [B \cdot j]dv, \qquad (1)$$

where:

df – force's vector, which is influenced on the element of current with volume *dv* in magnetic field with magnetic induction *B* and current density *j*.

The vector product in the right part of equality is showed that electromagnetic force is perpendicular to the direction of magnetic induction and current density (by left-hand rule).

The force, which acts on the winding or its part, can be calculated by integrating the equation (1):

$$F = \int_V [B \cdot j] \, dV \tag{2}$$

If B and j are perpendicular to each other and they are constant throughout entire volume, then electromagnetic force, which is influenced on the element of current in magnetic field:

$$F = B \cdot l \cdot i, \tag{3}$$

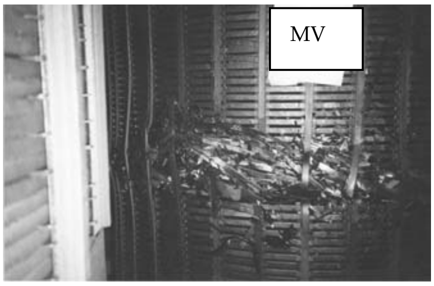
where:

l – length of wire or winding;

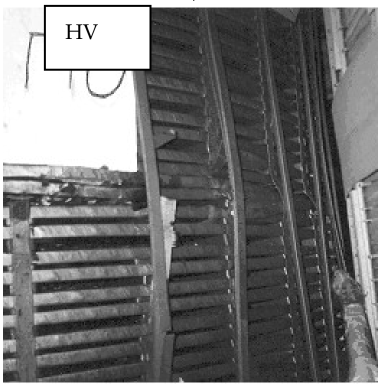
i – value of current into wire or winding;

B – value of magnetic induction.

Radial buckling in Medium voltage (MV) 220 kV winding (a) and in High voltage (HV) 500 kV winding (b) of 167 MVA/500 kV/220 kV autotransformer after three short-circuits in service is in the fig.5.



a)



b)

FIG. 5 AN EXAMPLE OF RADIAL BUCKLING IN MV 220 KV WINDING (a) AND IN HV EXTERNAL 500 KV WINDING (b) OF 167 MVA/500 KV/220 KV AUTOTRANSFORMER AFTER THREE SHORT-CIRCUITS AT 500 KV SUBSTATION IN SERVICE.

250 MVA /110 kV transformer was switch off by relay protection at the Heat Electric Power Station.

Turn-to-turn internal short-circuit in LV winding was detected after dismantling at the transformer manufacturer (the fig. 6). The probable cause of internal short-circuit was metallic object, which may be get to the channel between HV and LV windings.

FIG. 6 TURN-TO-TURN INTERNAL SHORT-CIRCUIT IN LV WINDING OF 250 MVA /110 kV TRANSFORMER AT THE HEAT ELECTRIC POWER STATION.

125 MVA/220 kV/110 kV autotransformer was switch off by gas relay protection after internal short-circuit at the "Kostroma-2" substation in service. The tank of autotransformer was not deformed (fig.7). Serious deformations and turn-to-turn internal short-circuit were detected in MV 110 kV winding, regulating winding and LV winding by LVI-testing, short-circuit inductive reactance measurements and iron core losses methods. LVI oscillograms of MV 110 kV winding, including turns of regulating winding (a), and oscillograms of LV winding (b) are in the fig.8. The LVI amplitude-frequency differences of "C" phase from "A" and "B" phases are noticeable. The short-circuit inductive reactance differences of "C" phase from "A" and "B" phases are Δ Xk= -11,6% in MV-LV winding regime, and Δ Xk= -7% in HV-LV winding regime.

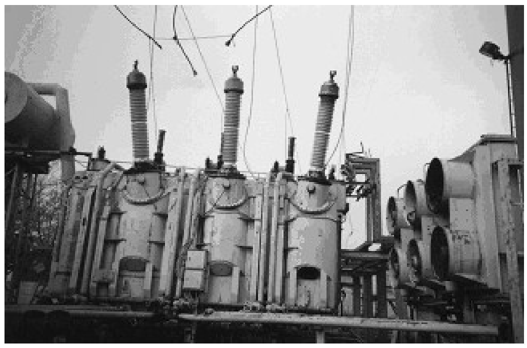
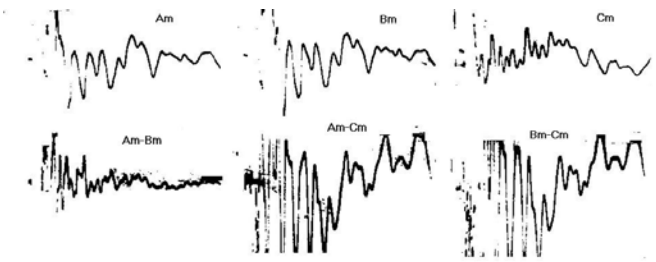
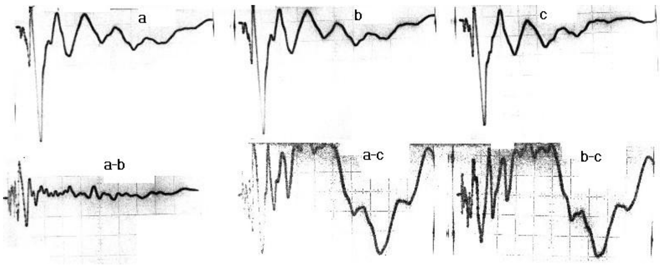


FIG. 7 125 MVA 220 KV/110 kV AUTOTRANSFORMER AFTER INTERNAL SHORT-CIRAT AT "KOSTROMA-2" SUBSTATION.



a)



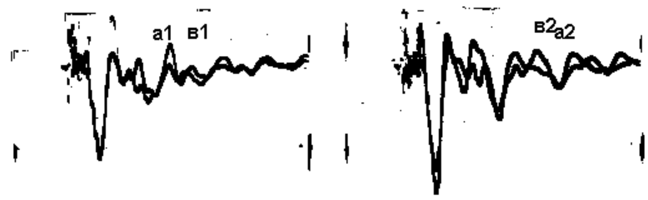
b)

FIG. 8 LVI OSCILLOGRAMS OF MV 110 kV WINDING, INCLUDING TURNS OF REGULATING WINDING (a), AND OSCILLOGRAMS OF LV WINDING (b) OF 125 MVA/220 kV/110 kV AUTOTRANSFORMER AFTER INTERNAL SHORT-CIRAT AT "KOSTROMA-2" SUBSTATION, ILLUSTRATING AMPLITUDE-FREQUENCY DIFFERENCES OF "C" PHASE .

The main goal of diagnostic investigation of 125 MVA 220/110 kV autotransformer was to define the possibility of repairing. On the basis of results of this diagnostic investigation there was planed the substitution of autotransformer.

The block 80 MVA 110 kV transformer had serious amplitude and frequency LVI LV1-LV2 winding oscillogram differences after generator side short-circuit at Heat Electric Power Station. The LV- winding signal spectrum of 80 MVA 110 kV transformer changed after short-circuit. The original 300 kHz, 500 kHz, 700 kHz resonance frequencies disappeared and a new 400 kHz, 800 kHz resonance frequencies appeared in the FRA spectrum. The LVI-tests and spectrum analysis of 80 MVA 110 kV transformer's LV-windings detected axial electrodynamic deformations.

The 40 MVA 110/35 kV power transformer was faulted after 35 kV side short-circuit with the fire and destruction of porcelain bushings. The single-phase 60 MVA 220/110 kV autotransformer at "Kinel" substation was switch off by relay protection in service. The LVI-testing of these transformer's windings detected residual deformations of "A" phase. LVI lay oscillograms of two LV parallel windings – faulted "A" phase and not faulted "B" phase (a), not faulted "B" and "C" phases (b) are in the fig.7. The LVI amplitude-frequency differences of "A" phase from "B" and "C" phases are noticeable (fig.9).



a)

b)

FIG. 9 LVI LAY OSCILLOGRAMS OF TWO LV PARALLEL WINDINGS – FAULTED "A" PHASE AND NOT FAULTED "B" PHASE (a), NOT FAULTED "B" AND "C" PHASES (b), ILLUSTRATING AMPLITUDE-FREQUENCY DIFFERENCES OF DEFORMED "A" PHASE OF 60 MVA 220/110 kV AUTOTRANSFORMER.

The residual electrodynamic deformations of LV winding have been detected at 32 MVA 110 kV transformer, using LVI-testing and short-circuit inductive reactance measurements. This 32 MVA transformer was used in the Heat Electric Power Station for power station internal needs. The LVI-testing and short-circuit inductive reactance measurement has been carried out after one of the difficult short-circuit at the 6 kV side, which has happened because of insulation disruption of 6 kV cables. The amplitude-frequency differences have been detected in the LVI oscillograms of low-voltage winding. These differences were from 0,4 volt to 0,8 volt. The LVI oscillograms, which were recorded after short- circuit (faultgrams), were being compared with LVI oscillograms, which were recorded before short-circuit (normograms) [5, 6, 7, 10-17].

Diagnostics experience was showed that the transformer plant documentation should be include: normograms of LVI-testing or FRA spectrums, data bases of partial discharge technique, normograms of infra-red diagnostics (for first models) during heat testing, data bases of winding pressure by vibration measurements of transformer. Short-circuit reactance measurements (Zk) and LVI-testing should be carry out together. The necessity of LVI-normograms (FRA) of all new manufactured transformer with capacity over 2,5 MVA, which are produced at the transformer manufacturers, is came. It's necessity for data bases of the mechanical winding conditions for the future LVI-testing (FRA) at the energy system after

probable short-circuit. LVI-testing is necessary for all transformers after short-circuits, for new transformers, for transformers after repairs at all energy systems [8, 9, 15-17].

Information-measuring System for Control of Inductance Value Transformer's Winding

The most important element of Information-measuring systems is the system of monitoring the parameters of electrical of equipment [3, 17-19].

The residual winding's deformations of power transformers during short circuits will be appear practically instantly, without leaving time fo analysis the results of the diagnostic measurements, and requiring as it is possible rapid switch off with the purpose averting or reduction in the scales future repairing of electrical equipment.

Information-measuring systems (IMS), which described in this paper, were proposed to use together with rapid digital protection against short-circuit regimes in transformer windings. The instantaneous and average values of inductance were calculated. This calculation was showed that IMS, using for inductance value (L) control, allowed to decrease failure volume and expenditures for renovation repairing at transformer manufacturer.

Scheme of IMS for the control the state of transformer's winding in service without switch off from the network is depicted in Fig. 10 [1-4, 17-18].

Algorithm of Information-measuring system (IMS)

The algorithm of IMS's work is the following. The continuous control of the winding's condition state of the controlled power transformer is ensured by a constant determination of the significance of inductance's deviation from the base value of inductance, which is taken from the block of the base inductance.

During the work of the three-phase controlled power transformer (T) for the three-phase resistive load (Load) is made the measurement of the value of primary voltage U1 by measuring converters primary voltage (high-voltage transformers TV1).

Signal from the converters was entered to the entrance of the block of bringing the primary voltage to the second. In this block the value of the primary voltage, which is corrected to the second, is calculated:

$$\dot{U}_1 = \frac{U_1}{K_t} \tag{4}$$

where:

Kt - known given value of the transformation ratio of power transformer.

Signals from the measuring converters of second voltage (voltage transformers TV2) and signals from the output of the previous block were entered to the entrance.

In the block of calculation of voltage difference, which corrected to the second side, it is determined:

$$\Delta\dot{U} = \dot{U}_1 - U_2 \tag{5}$$

where:

U2 - the value of second voltage, measured by converters TV2.

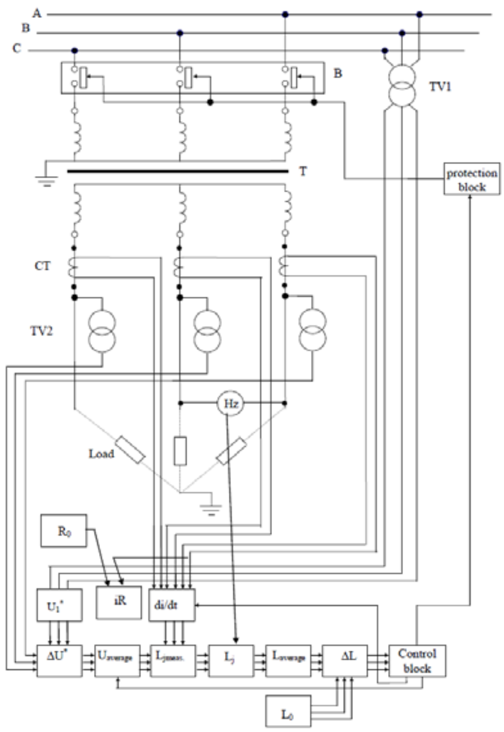


FIG. 10 INFORMATION-MEASURING SYSTEM FOR CONTROL OF TRANSFORMER'S WINDINGS STATE IN SERVICE.

The calculation is produced in the assigned time interval in the block of calculation of voltage's average value:

$$\dot{u}_{average} = \frac{\dot{u}_j(t_2) + \dot{u}_j(t_1)}{2} \tag{6}$$

where:

uj- value between corrected to the second side voltages on the transformer;

t1 and t2 - temporary boundaries of partition's interval.

In the block of calculation of the current derivation is calculated the increase of the current in the assigned time interval:

$$di_j / dt = \frac{i_j(t_2) + i_j(t_1)}{t_2 - t_1} \quad (7)$$

ij - value of current in the secondary winding of controlled transformer, measured by current converters (current transformers CT).

In the block of calculation of inductance the instantaneous value of inductance is determined in the assigned time interval:

$$L_{j\,meas.} = \frac{\dot{u}_{average}}{(di_j / dt)} \quad (8)$$

where:

$u_{average}$- average value of voltage,

dij/dt- value of current derivation.

Expression (8) can be obtained from Ohm's law for the magnetic circuit:

$$\psi = Li \quad (9)$$

Further using expressions:

$$\mathrm{u} = -\frac{d\psi}{dt}; L = \frac{\psi}{i}, \quad (10)$$

we obtain $d\psi = Ldi + idL$.

Disregarding second term (L=const), we have with the linear characteristic of the medium:

$$\mathrm{u} = L\frac{di}{dt}, \quad (11)$$

which is analogous to (8).

In the block of bringing the value of inductance to the nominal frequency the instantaneous value of inductance, with corrected to the nominal frequency, is calculated:

$$L_j = L_{j\,meas.} \frac{f_{meas.}}{f_{nom.}} \quad (12)$$

where:

$f_{meas.}$ - measured by frequency converter value of the frequency (Hz),

$f_{nom.}$ - nominal value of the frequency.

$L_{j\,meas.}$ - instantaneous value of inductance.

In the following block the average value of inductance during each period is calculated:

$$L_{average.} = \sum_{j=1}^{N} L_j / N \quad (13)$$

In the block of calculation of deviation is produced the comparison of $L_{average}$ value during the period with the base L0 value and their difference is calculated:

$$\Delta L = \frac{(L_{average} - L_0) \cdot 100\%}{L_0} \quad (14)$$

$L_{average}$ - the average value of inductance during the period;

L_0 - the base value of transformer inductance, determined by calculations also according to the results of preliminary experiment.

In the case of the beginning of winding deformations, and also in the case of winding turn-to-turn internal short-circuit the value of inductance L is developed to increase, or to decrease from period to next period that accompanies the irreversible destruction of the controlled power transformer's windings.

Than the signal from the control block enters to the protection block (rapid digital protection), where signal to switch off in high-voltage circuit breaker (B) is formed. And than Information-measuring system and connected with it protection block were stopped the process of winding destruction [1-4, 17-20].

Conclusions

The low voltage impulse testing is a very sensitive and reliable method of deformation's detections of transformer windings. The LVI oscillograms are a "fingerprint" of transformer.

This winding "fingerprint" are defined by major resonance frequencies (a winding spectra). The 250 MVA 220 kV winding transformer's FRA spectrum was contained a 110 kHz, 320 kHz and 550 kHz frequencies, which are changed 1.3-2 times after the mechanical radial winding deformations. The FRA spectrum of 80 MVA 110 kV transformer changed after short-circuit. The original 300 kHz, 500 kHz, 700 kHz resonance frequencies disappeared and a new 400 kHz, 800 kHz resonance frequencies.

Infra-red control was effective for detection electrical equipment's faults, defects and weaknesses: overheating of disconnector contacts, bushing condition of power transformers, condition of circuit breakers, arresters and limiters of overvoltages, coupling transformers, measuring current

transformers, measuring voltage transformers, control of connecting heads soldering quality of turbo-generator stator windings.

The most important element of Information-measuring systems is the system of monitoring the parameters of electrical of equipment.

The residual winding's deformations of power transformers during short circuits will be appear practically instantly, without leaving time on the analysis the results of the diagnostic measurements, and requiring as it is possible rapid switch off with the purpose averting or reduction in the scales future repairing of electrical equipment.

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At the beginning of winding deformations, and also in the case of winding turn-to-turn internal short-circuit the value of inductance L is developed to increase, or to decrease.

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2. Power transformer's fault diagnostics at SAMARAENERGO Co, including FRA/LVI method. Vaxjo , Sweden, 2000.

3. The technical diagnostics, damages and resource of power and measurement transformers, reactors. Moscow, Russia, Energo-Atomizdat publisher, 2007.

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